FUZZY LOGIC IN ACTIVE MAGNETIC BEARING CONTROL

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ABSTRACT

Active magnetic bearings are special bearings for demanding applications. With modern hardware and sophisticated control methods the problems, that arise from the nonlinear structure of the active magnetic bearing system, can be overcome. In this paper a fuzzy derivate gain adjusting method for active magnetic bearing control is presented. The method is based on the error and error derivate signals that are used as the basis of the fuzzy inference. With this method the effects of the vibration noise can be decreased. To achieve adequately high sampling rate for the control algorithm a powerful digital signal processor (DSP) was used in the experiments.

INTRODUCTION

Active magnetic bearings (AMB) have proofed to be an attractive technology in applications like turbo molecular pumps, flywheels for energy storage, reaction wheels for attitude control of artificial satellites, the main shafts of electric motors of tool machines and turbo compressors [10,11,12]. However, due to the non-linearities the control of the AMB system is a demanding task.

The idea of applying fuzzy logic in dynamic system control has been studied since mid seventies [9] and during the past few years it has emerged to be one of the main application fields of the fuzzy set theory [8]. Although fuzzy logic control can be applied to well-defined systems, the best results have been reported from systems that are non-linear or ill-defined [7,8]. In active magnetic bearing control field not so many fuzzy logic control experiments have been seen yet, although some work has been done [1,4,5,6]. In this paper a fuzzy derivate gain adjusting method for AMB control is presented. The method is based on the error and error derivate signals that are used as the basis of the fuzzy inference. The approach provides a powerful method to the elimination of the vibration noise effects and rotational speed estimation.

The AMB system requires very short sampling time when the controller is implemented digitally. The high sampling frequency demands very powerful hardware solutions like digital signal processors [2]. In our experiments the implementation of fuzzy logic inference with DSP gives a flexible solution to the control of AMBs.

ACTIVE MAGNETIC BEARING SYSTEM

A complete active magnetic bearing system consists of controller with position sensor, current amplifier and magnetic bearing itself. The test system configuration used in our experiments can be seen in the Fig. 1. The electric motor was a test machine of 42 kW of power and rated speed of 42,000 RPM. The details of the electronics is discussed later in this paper.

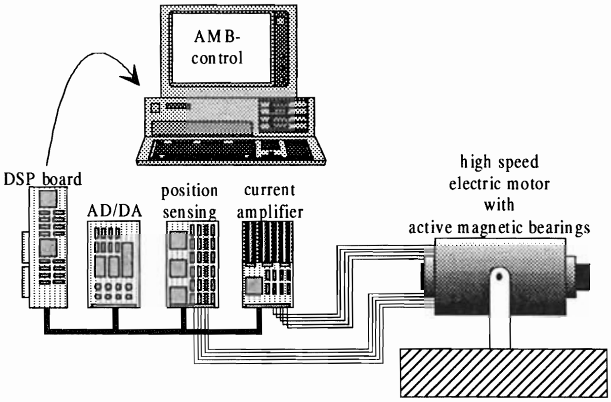

FIGURE 1: The AMB test setup

Electro-mechanical part

The electro-mechanical part of the AMB system consists of rotor that is hovering between the electric magnets. Mathematically, the electro-mechanical part of the AMB system can be described using force equation. The force equation can be linearized at the operating point and it becomes

$$m\ddot{\delta} - K_b\delta = K_i i + F_e \qquad (1)$$

where m is the lumped mass of the rotor, δ is is the air gap between the shaft and the electric magnet, F_e is the external disturbance force, K_i is the current gain and K_b is the position stiffness. The force equation can be presented as a block diagram (Fig. 2) where we can see clearly that the position stiffness or spring constant is negative. Therefore the magnetic bearing has always to be feedback controlled. This linear model was used as a part in the simulations carried out by *Simulink* program.

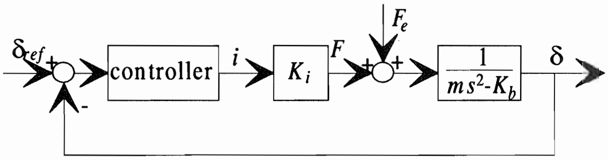

Figure 2: The linear block diagram of the AMB system

Control electronics [6]

Control electronics consists of the current amplifier, position measuring device, converter board, digital signal processor (DSP) board and PC-compatible computer. The PC is equipped with a communication software that is used to load and start programs in the DSP and to view and change the parameters of the controller program in the DSP. The DSP board is plugged in a 16-bit ISA slot of the computer. The converter board is connected to the peripheral interface of DSP board. From the converter board output voltage is fed to the current amplifier. The current amplifier drives the coils of the magnetic bearing. The position of the rotor is measured with a position sensor that provides a position signal to the AD input of the converter board.

The position sensing device is based on inductance variation sensor. The device converts the distance between rotor and sensor end to voltage ranging from -2 V to 2 V. The converter board has eight filters, eight analog-to-digital (AD) channels, eight digital-to-analog (DA) channels, an address decoder and a DC/DC-converter. The incoming analog signal is first filtered with the anti-aliasing filter to attenuate frequencies above Nyquist rate. After that the signal is fed directly to the AD-converter chip that includes a multiplexer for eight channels, a sample and hold circuit, one AD-converter, channel select logic and interface to the microprocessor. Channel is selected by address lines and chip select signal. Address lines are brought directly from processor and chip select is generated from upper address lines by address decoder. After selecting channel conversion can be started at any time. AD-converter signals to processor when conversion is ready and new conversion can be started. Conversion result is 10 bits wide. Maximum throughput rate for one channel is 200 000 samples per second. If all 8 channels are on use, the throughput rate for one channel is 25 000 samples per second. The input voltage range is from -2.5 V to 2.5 V.

The DA-converter consists of two components. There are two four-channel DA-converter to produce an eight channel DA-converter. In one DA-converter there is a voltage output DA-converter of 12-bit resolution, output register, channel select logic and microprocessor interface. Voltage range is at maximum from -10V to +10V. Throughput rate is 200 kHz and it is not dependent on the number of the channels used. Right channel is selected with two address lines from processor and chip select signal from address decoder. Data is then written and latched to the output register. The DC/DC-converter generates all voltages needed in converter board, both positive and negative.

The signal processor board of the test setup was a SPIRIT30-board made by Sonitech inc. Board exploits Texas Instruments' TMS320C30-33 digital signal processor with 64K words (32 bits) of zero wait-state memory, peripheral interface, two serial channels, interface for memory board and 16-bit PC-bus interface. Memory can be expanded up to 160K words. The communication between DSP-board and host-PC is provided through I/O and DMA-interface and the maximum transfer rate is 3.3 Mbytes. Parallel I/O-interface is a subset of the expansion bus of the DSP-processor. The interface includes 16-data bits, 13-address bits and several control signals. With this parallel interface connector the converter board is connected to the signal processor board. Converter board needs at least three wait states from signal processor to function properly.

The current amplifier is a two-channel voltage controlled current source. Voltage is fed to the input and the amplifier controls the output current according the control voltage. The power stage is a double feed forward type and it is made with power FETs and diodes and it is controlled by current mode switching regulator. The switching frequency of the regulator is as high as 25 kHz.

In the near future the signal processor board will be replaced with a stand alone DSP-board, that exploits TMS320C31 digital signal processor. The board is equipped with a SCSI or CAN interface.

CONTROL OF THE ACTIVE MAGNETIC BEARING SYSTEM

The most common primary control algorithm for an AMB is a PID-controller. With a PID-controller both the demands of the dynamic properties and the steady-state accuracy of the AMB system can be fulfilled [12]. However, some problems come up when ordinary PID-controller is used. The unbalanced rotating shaft fluctuates sinusoidal according to the rotating speed of the shaft and generates noise in the air gap measurement. Even a small eccentricity e in the shaft can cause troubles in the stability of the system due to the derivate term of the controller, because the PID-controlled system has high stiffness when the rotating frequency ω exceeds the system natural frequency ω_n (Fig. 3). Usually some kind of compensator circuit has to be added to the system to meet the dynamic demands especially at high frequency range. Unfortunately, the compensator circuitry can become very complicated and hard to tune.

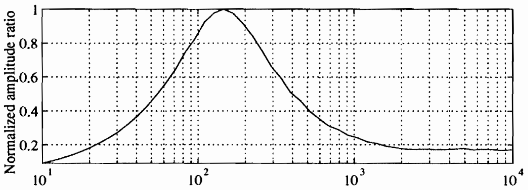

Figure 3: The vibration amplitude dependence on the rotating frequency

Fuzzy control structures

There are several potential possibilities to apply fuzzy logic in the control of an AMB. The first possibility is the use of a basic fuzzy logic controller (FLC) which can be considered as a traditional way of utilizing fuzzy logic in a control system (Fig. 4). The FLC in its traditional form was presented by Mamdani in his pioneer work in early seventies [9]. His idea has widely adopted and it has been used to control almost everything from steam engine [9] to hydraulic position servo [7].

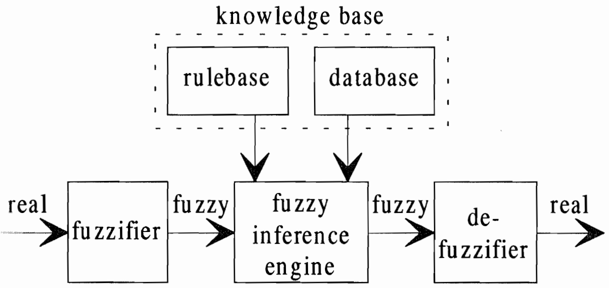

Figure 4: The basic structure of the FLC

The fuzzy logic controller in its basic form has been the most successfully applied in systems that are non-linear, ill-defined or which are best controlled by human operator [8]. However, the systems, which can be mathematically modelled and controlled with the methods of the modern control theory, do not benefit much from fuzzy logic control approach [8]. In spite of the intense research work in this field the tuning of the FLC is still based almost merely on trial and error and it is therefore rather cumbersome. The stability and accuracy analysis of the FLC lacks comprehensive and practicable methods and tools. So, the traditional fuzzy logic controller is perhaps not the most suitable control structure for the active magnetic bearings.

A different approach to use fuzzy logic in control systems is to use fuzzy logic as an auxiliary part of the system when the normal controller acts as the primary controller. This kind of approach is advantageous in systems like the AMB control; the conventional PID-controller can be tuned and tested as normally and the fuzzy logic part helps with the difficult situations. One possible method is to use the gain scheduling adaptive control scheme. In the next chapter one potential control structure based on this gain scheduling method is presented.

Fuzzy adaptation of the derivate gain

As stated above, the derivate gain of the PID-controller can be a source of vibration due to noise in the displacement signal caused by the unbalanced shaft. The derivate control of a conventional PID-controller can be modified using fuzzy logic so, that the effects of the noise can be minimized [1,4,5,6].

The problem with the PID-controller is a bathtube shaped magnitude response [1]. The high gain at low frequencies is desired because stiffness improves the behavior during the start-up and on the other hand the noise is no problem. But the increased gain at the high frequencies makes the system sensitive to the noise. So, the high gain at low frequencies should be maintained and at the same time, the gain at the high frequencies should be decreased.

One method to decrease the gain at the high frequencies is to change the derivate gain as a function of the rotating speed. However, this method requires the rotating speed to be measured and it is not desirable to increase the amount of sensors. A more sophisticated approach is to use displacement and speed that are needed anyway. The decision how to alter the derivate gain using only displacement and speed can be made with fuzzy rules [1,4,5,6].

The rules can be derived using the engineering knowledge about the system. The basic assumption is that when the absolute value of the speed is big the system is operating at high frequencies and the derivate gain should be reduced [1,4,5,6]. When the absolute value of the error (displacement) is big and the absolute value of the speed is also big the system is apparently heavily vibrating and the derivate gain should be reduced strongly [1,4,5,6]. The rule-base of the system is presented in the Fig. 5.

		Error	
		small	big
Error derivate	small	high	high
	big	med	low

Figure 5: The rule-base for derivate gain adaptation

A simulation model was build to test the idea of the fuzzy adaptation of the derivate gain of the PID-controller (Fig. 6). The electro-mechanical part of the AMB system was modeled as a linear system (Fig. 2). Because the time constants of the control electronics are much smaller than those of the electro-mechanical part, they were modeled as gains. The simulations were done using *Simulink* and *Matlab* programs. The membership functions used in the simulation may be seen in the Fig. 7. The applied fuzzy inference method was the simple Min-Max mechanism proposed by Mamdani [9]. The defuzzification operation used in the simulation was the common center of gravity strategy.

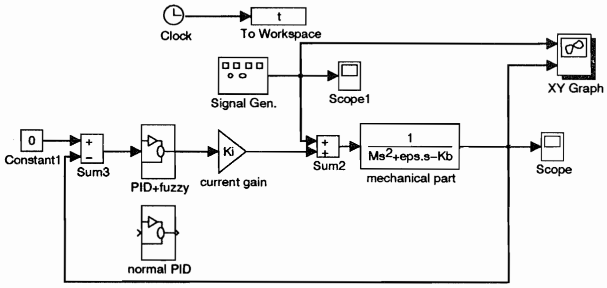

Figure 7: *Simulink* model of the system

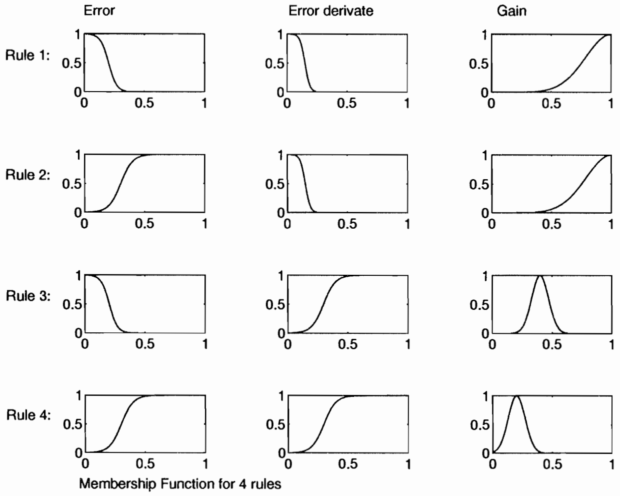

Figure 7: The membership functions and the rule base.

In the Fig. 8 amplitude responses of closed-loop system simulations of both normal PID-controller and PID-controller with fuzzy derivate gain adaptation can be seen. The normal PID-controlled system has small amplitude both at low and high frequencies and an amplitude peak at the natural frequency. The fuzzy derivate gain adjusting controller has small amplitude at low frequencies but at high frequencies the amplitude is bigger than with normal PID-controller. The conclusion of the simulations is that the behavior of the fuzzy derivate gain adjusting controller fulfills the expectations and the audible noise problem can be solved with this approach.

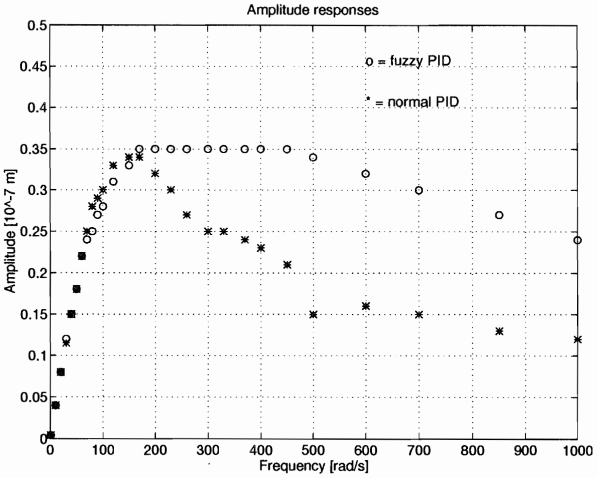

Figure 8: Simulated amplitude responses of the closed loop system.

CONCLUSIONS

In this paper a fuzzy derivate gain adjusting method for active magnetic bearing control was presented. The method is based on the error and error derivate signals that are used as the basis of the fuzzy inference. The simulations show that with this method the effects of the vibration noise can be decreased.

The implementing issues are the main concern of the fuzzy logic control of the active magnetic bearing systems. The AMB system requires very short sampling time when the controller is implemented digitally. Usually a sampling frequency of 10...15 kHz is appropriate. This high sampling frequency demands very powerful hardware solutions and yet the timing can be critical especially if any additional calculations are needed. A very common situation is that the position measurement signal has to be digitally filtered to get a proper and feasible signal for the control algorithm. These filter algorithms along the fuzzy inference – although the max-min fuzzy inference is computationally quite simple – induce very difficult timing problems.

An other problem arises with the derivate action of the controller. If we want to avoid erroneous derivates, the signal has to be very smooth. In practice this means that the signal has to be properly filtered. On the other hand, high sampling frequency means also long word length in computing derivates [3] which places more demands on the hardware.

Although the fuzzy derivate gain adjusting method for PID-controller has been applied in the control of AMB-system, it could be used in other application fields too. The idea of using the fuzzy inference as an auxiliary part of the traditional controller – a PID-controller in this case – is advantageous compared to the direct FLC in systems where existing controller requires only a little improvement.

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